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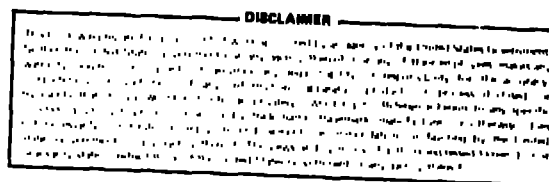
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RECOVERY OF MINERALS FROM U.S. COALS*

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Summary

Projections show that domestic coal will serve for the majority of energy supplies during the next decades. Thorough chemical cleaning of this coal can be accomplished in long residence time, slurry transport systems to produce high-quality fuel product. Concurrently, mineral recovery from coals will supplement existing ores.

This paper describes this concept and gives preliminary engineering considerations for mineral recovery during transport operations.

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Introduction

Only a few decades ago, coal served as the major energy source within the United States and, once again to meet future energy needs, increased coal production can readily come from large, proven domestic resources (1). Clearly, that increase in coal utilization must occur concurrently with continued technology development so that the firm national commitment to protect the environment is sustained. During the last decades, coal technology has evolved over a broad front. Some current technological approaches to coal utilization problems are costly both in capital and in operating energy requirements. Ideally, systems require acceptable capital demands and restricted energy consumption during operation. These factors are important throughout the coal utilization cycle, including during transportation.

Current coal technology makes extensive use of existing transportation systems through several corridors. U.S. railroads and barge systems ship large tonnages of coal and fuel ores, but expanded coal production may exceed the capacity limit of existing systems. Coal now is also being moved between production and utilization regions through slurry pipelines (2). For this demonstrated technology (3,4), the coal is first ground. The ground coal is admixed with a fluid to form a slurry which is pumped to the market area. Slurry pipelines demonstrate considerable savings both in capital expense (5), as compared with new rail systems, and operating energy, as compared with current haulage energy demands as met through diesel electric rail locomotives (6).

During the last decades, attention has been repeatedly focused on estimates of world-wide petroleum reserves (7). Although petroleum demand has slackened temporarily, reserve estimates for the total quantity of recoverable light crudes have not significantly altered since Hubbert's review. Accompanying that real limit to petroleum supply is a parallel situation in supply for ores of many important minerals (8). High grade ores are in increasingly short supply and several major ore types have been extensively depleted (Figure 1) (9,10). These facts do not suggest that mineral production will be terminated momentarily. Rather, lower-grade ores, both fuel ores and mineral ores, must now be addressed. To some extent, the renaissance in coal utilization reflects this trend: coal, a fuel of 10,000 Btu/pound is replacing petroleum, a fuel of 18,000 Btu/pound. Coal as produced contains a suite of trace elements and minor mineral constituents. These "impurities," although typically low in concentration, represent a large tonnage due to the fact that coal production is so large. These minerals could not normally be considered ores except for the fact that coal is now being produced.

Slurry pipeline systems offer promise for mineral production during transportation by extraction of low-level minerals from coal (11). Separating these minerals from the fuel components leaves a low-sulfur, premium fuel product. Such "clean" coal could be burned in conventional combustion facilities with minimal environmental impact and requirements for flue gas desulfurization (FGD). Mineral recovery may contribute to the total economic return for this system; it could well lead to a "new" source of metals necessary for commerce and defense.

This paper describes this concept and gives preliminary engineering results for the possibilities of using long-distance, long residence time slurry pipelines as systems for chemical coal cleaning.

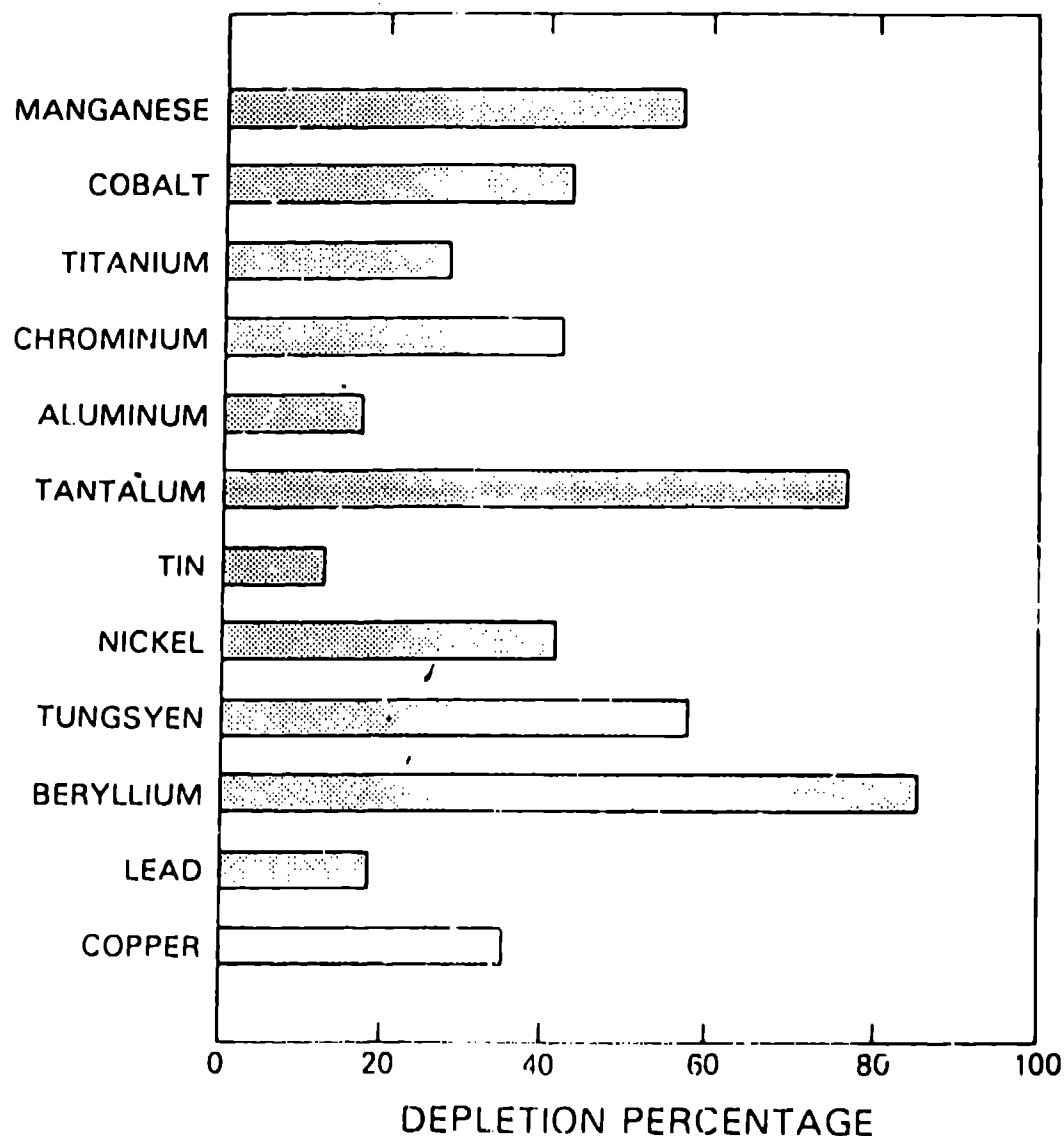


Figure 1 - These data, tabulated from U.S. Bureau of Mines, show the fraction of world-wide, high-grade ore that has been utilized (1975).

Coal as a Mineral Ore

Coal is a complex mixture of minerals types admixed with a carbon-rich polymeric matrix. Analysis of coal composition is complicated since high-quality coal is frequently mixed with carbon-poor strata; consequently feed coal may alternate between highly mineralized materials, rather like the surrounding rocks, and high-carbon, low-"ash" material. Likewise, mining machinery at times cuts into the mine roof (back) or floor, thereby lowering coal quality. Resulting product coal is of varying quality, depending strongly upon both the seam geometry and mining operation control. Coal that services utilities is blended to yield an average run-of-the-mine (ROM) material.

ROM coal can be shipped as it is produced, or it can be processed to improve its technological usefulness. Coal preparation, i.e., cleaning the coal to remove inorganic constituents, has had wide technological development, but only limited deployment (12). At present, approximately 15% of the nearly 600 million tons of coal used annually by the utility industry is cleaned. Generally, cleaning is completed only to a small

degree. The rest is burned as produced, and subsequent chemical processing is used to remove pollutants from flue gases, when required. Pollutants result in the main from the minerals incorporated within the feed coal. Considerable interest persists to extend coal cleaning technologies due to 1) escalating prices for coal and for coal transportation, 2) apparent decreasing coal quality (as reflected in increasing ash content, due to less selective mining techniques and exploitation of lower quality seams, and 3) capital intensive nature of FGD systems and the necessity for utilities to limit capital investments (12).

Coal cleaning technologies exploit either physical or chemical techniques. Physical cleaning relies on gravity separation, froth flotation, or magnetic separation to segregate the less dense coal constituents, such as relatively pure organic "coal" (with a specific gravity under 1.5) from less pure coal containing or mixed with mineralized constituents, such as pyrite, FeS_2 , with a specific gravity of 4.80 to 5.20.

Extensive work has explored coal mineralogy (13,14). Mineral constituents vary widely in physical size. Iron pyrites, at times, are found as discrete lenses that weigh several kilograms (14). On the other extreme, discrete mineral constituents are distributed widely through coal on a micro-scale. In fact, detailed microscopic investigations show micro-mineral phases at the limit of optical observation, smaller than 1×10^{-6} cm. Similar crystalline habits are evident for both large-scale and micro-scale constituents. Feed coals contain a wide range of minerals and wide range of mineral content, from approximately 4 to 30%, depending to a large extent upon the discrimination of the mining procedure and the nature of the coal seam.

Since coal contains 70% or higher carbon by weight, other mineral types are not concentrated, for coal is chosen as a carbon-rich mineral. Thus, most elements found in ROM coal occur in less concentration than "average" crustal abundances (15). Only specific elements of normally low crustal concentration (namely boron, chlorine, selenium, and arsenic), which are concentrated in coal because of geochemical processes, have higher average concentrations in coals than within the earth's crust. Of course, enhanced mineral concentrations are apparent at the top and bottom of a coal seam, but these deviations are not apparent in ROM coal samples. Thus, coal is a low-grade mineral ore for most metals of economic importance. But the major cost of mineral extraction may be covered by concurrent processing for fuel content, and specific seams may show concentrations for higher-than-average values.

Table I lists data that describe the elemental composition for two coal types, "Eastern" and "Western" coals. The Eastern data represents averages obtained for Appalachian and Illinois Basins steam coals and the Western lists averages of several Rocky Mountain coals (13). Data were chosen to typify fuels that now serve as utility stocks. Data show that coals from the East are more highly mineralized than the Rocky Mountain coals. This apparent variation in mineral content may result as much from the relative ease in separating carbon-rich materials from the mining environment as from any inherent differences between coal types, for Eastern seams are often thin and dispersed with mineral stringers, while Western seams are frequently mined as surface operations utilizing thick seams where selection is optimized.

Data in Table I show major elements, those in average concentration of greater than 1%, minor elements, those between 500 and 10,000 ppm (1%), and finally trace elements, those between 10 and 500 ppm (13). Other data

Table I. Elemental Composition of U.S. Utility Coals

Element		Eastern Coal	Western Coal	
Carbon	C	71.0 %	67.0 %	Major Elements
Oxygen	O	8.1 %	17.0 %	
Hydrogen	H	4.9 %	4.7 %	
Sulfur	S	3.0 %	0.760 %	
Nitrogen	N	1.3 %	1.0 %	
Silicon	Si	2.6 %	1.7 %	
Iron	Fe	1.8 %	0.53 %	
Aluminum	Al	1.5 %	1.0 %	
Calcium	Ca	0.57 %	1.70 %	Minor Elements
Chlorine	Cl	0.16 %	0.030 %	
Potassium	K	0.21 %	0.050 %	
Magnesium	Mg	0.050 %	0.140 %	
Sodium	Na	0.050 %	0.140 %	
Titanium	Ti	0.070 %	0.050 %	
Arsenic	As	20. ppm	2.30 ppm	Trace Elements greater than 10 ppm except as noted (*)
Boron	B	76. ppm	56. ppm	
Barium	Ba	150. ppm	500. ppm	
Bromine	Br	13. ppm	4.7 ppm	
Cerium	Ce	20. ppm	11. ppm	
Chromium	Cr	19. ppm	9. ppm	
Cobalt	Co	8. ppm	1.8 ppm	
Copper	Cu	16. ppm	10. ppm	
Fluorine	F	78. ppm	62. ppm	
Manganese	Mn	36. ppm	49. ppm	
Molybdenum	Mo	6.4 ppm	2.1 ppm	
Nickel	Ni	18. ppm	5. ppm	
Phosphorus	P	117. ppm	130. ppm	
Lead	Pb	19. ppm	3.4 ppm	
Rubidium	Rb	21. ppm	4.6 ppm	
Strontium	Sr	83. ppm	260. ppm	
Uranium	U*	1.5 ppm	1.2 ppm	
Thorium	Th*	3.3 ppm	2.3 ppm	
Vanadium	V	35. ppm	14. ppm	
Tantalum	Ta*	0.15 ppm	0.33 ppm	
Tungsten	W*	0.82 ppm	0.69 ppm	
Zinc	Zn	138. ppm	7. ppm	
Zirconium	Zr	46. ppm	33. ppm	

Data from Reference (13). Eastern coal represents an arithmetic average of Appalachian and Illinois basins to depict an average ROM produced in the Eastern U.S., while Western coal is a composite average of several Rock Mountain feed coals.

sets (11) show far more complete information on low-level trace elements but that level of detail is not important here. Moreover, several low-level elements, thorium, uranium, and tungsten, have been included because of obvious technological interest, even though they occur in less average concentrations than 10 ppm. Most of these metals could not now be recovered at these low concentrations. However, gold, at 1 ppm, is thought economic even at current economies.

Considerable earlier work concluded that particular elements were selectively incorporated into coal fractions (organic fractions) and others were combined with mineral fractions (16,17). Associations were thought

to involve specific chemical bonding, say, with the organic fraction. Associative correlations resulted from trends apparent in coal washability data. Clearly, gravity separation (physical coal cleaning) leads to discrimination in mineral types. For instance, dense particles of pyrite separate from less dense organic fractions and some other sulfide minerals tend to concentrate along with the sulfide-rich fractions (13). However, these distinctions, rather like distinctions between sulfur types (18), remain operational definitions based on quantitative performance. In fact, more recent experience points to a model of coal as a mixture of organic rich material with discrete mineral phases (14). The extent of mixing is such that simple gravity separation cannot be entirely effective to sort organic from inorganic fractions. Extensive grinding, which is required for increased separation, leads to increased surface area and altered wetting characteristics. Physical coal cleaning, although highly developed, therefore has distinct limitations for thorough mineral separation (12).

Chemical removal of sulfur contaminants from coal has been demonstrated repeatedly. Surprisingly perhaps, sulfide mineral inclusions in coal are reactive and readily attacked through chemical action. Several processes using chemical oxidative attack appear effective. For example, processes that utilize molecular metal oxidants in conjunction with oxygen in aqueous solution appear effective in removing significant quantities of sulfur (19,20). "Organic" sulfur is oxidized:



as is pyritic sulfur, perhaps to sulfate:



(These reactions are not balanced since the mechanisms are only poorly understood; most likely a series of processes occurs.) Systems that utilize chlorine, molecular oxygen under either basic or acidic conditions, high pressure oxygen, or singlet oxygen (generated with an RF discharge) attack sulfide minerals. These reactions are not rapid--temperatures in the vicinity of 100°C for several hours are necessary. But sulfur is extensively converted to potentially soluble forms with these chemical cleaning procedures. The interesting questions raised by the chemistry of these techniques, especially why the oxidative processes preferentially attack sulfur compounds and not carbon, remain unanswered. Some heating value can be lost through formation of CO₂ during these oxidation processes.

Far less work has gone into understanding reactions of other accessory minerals than during chemical processes. Yet limited existing data show dissolution behavior that generally parallels sulfur dissolution. Mineral-release information resulted in the main from studies designed to clarify contaminant release during coal storage and from coal mining refuse. Data suggest that the acidic solutions, generated slowly through pyrite oxidation of coal-water mixtures, are effective in chemical leaching of much of the mineral ensemble in coals and coal wastes. These reaction conditions are utilized in chemical coal cleaning (19). (Similar highly mineralized solutions cause environmental problems within mining districts.) Although existing rate data concentrate on mineral release into aqueous solution, mass balances show that removal of 50 to 75% of the total amount of many trace elements can occur in 3/8 inch coal in 24-48 hours (16). The trace element dissolution processes are slow, caused in part by the inaccessibility of significant fractions of the finely divided mineral suite. Smaller particle size may enhance the cleaning process; in

fact, removal optimization has not been explored. We suggest that long residence time, slurry-transport systems make that production of clean fuel a technical possibility, for transit times of two to three days are common. Batch processing of such slow reactions would be prohibitively expensive, especially for a high-tonnage, low-value material (on a weight basis) as coal.

Slurry Transport Systems

Favorable economics for transporting solids in a fluid slurry have been apparent for decades. A coal slurry pilot was built in 1889 to demonstrate coal-water transport (4). Existing slurry systems had genesis in coal cleaning technology where gravity separations (physical cleaning) were effected using coal-water mixtures. It became obvious that cleaning-transport systems could be combined, "finishing" the cleaning operation through a dewatering step at the terminus, i.e., the power generating station. Thus, the idea of combining coal cleaning with coal transport was the major initial commercial emphasis for coal slurry transport systems (4).

The first commercial slurry line was constructed by Pittsburgh Consolidated Coal Company and was completed in 1957 (4). This 108-mile line was built in Ohio, connecting coal fields in southern Ohio to a generating station next to Lake Erie. The pipeline is fabricated of 10-3/4-O.D. steel pipe, buried 5 feet below the surface, that is, below the frost line. Velocity through the pipe is 4.5 feet/second (3.1 miles/hour). Another slurry-coal line, 275 miles long and 18 inch in diameter, services the 1580-MW_e Mohave Generating Station in Nevada (3). Velocity of this slurry transport system is 5.6 feet/second (3.8 miles/hour), resulting in a residence time of 72.4 hours.

High volume slurry pumps are well developed for service in the petroleum industry where such pumps deliver drilling muds (21). Because pumping work increases with viscosity, engineering improvements lower viscosity slurries by either increasing temperature, increasing the solvent fraction, or changing the solvent to another liquid that results in a less viscous mixture (22). Considerable experience shows that slurries are stable over long times; various chemical additives can be added to stabilize the mixture when required (23).

For purposes of illustration, consider the system outline in Table II. This transport system ships the average Eastern coal described in Table II, after suitable sizing, 200 miles--from the producing zone to the generating station. Transport is through 24-inch pipeline, constructed and designed

Table II. Slurry Transport Pipeline Model

FEED COAL:	Run-of-Mine, average Eastern coal/sized to pass 30 mesh
SLURRY MIXTURE:	50%/50% (v/v) Coal/Water; specific gravity 71.9 lb/ft ³
PIPELINE:	24 inch I.D., 200 miles long, insulated, largely buried underground
TRANSPORT:	Slurry, 2.2×10^3 ton/hour; coal 1.3×10^3 tons/hour
SERVICE FACTOR:	Pipeline operational 0.9 of year; moves 10^6 tons/year
TRANSPORT VELOCITY:	5.6 feet/second (3.8 miles/hour)

to transport 10,000,000 tons annually. This system, larger than those mentioned above, has a design velocity of 5.5 feet/second (3.8 miles/ hour) and average coal particles have a residence time during transport of 53.1 hours.

Chemical treatment of coals requires promotion of oxidative processes under acidic conditions. Exposure of coals containing sulfide minerals to oxygenated water begins a series of reactions that generate conditions sufficiently corrosive to attack ferrous materials. Current slurry practice dictates pH control for pipeline protection. Acidity is maintained at a pH of 5.5 or higher through the addition of sodium hydroxide. Oxygen is excluded, both at the initial slurry make up station and at pumping stations positioned along the pipeline. Thus, current pipeline technology, by design, maintains conditions to retard mineral dissolution.

Mineral Extraction Conditions

Existing data on coal mineralogy suggest that many of the accessory minerals, those described by the elemental composition shown in Table I, are converted to soluble species in the iron (III) sulfate solutions generated from pyrite oxidation. Although the mechanisms are still not known, oxidation by Fe (III) is probably involved. Under suitable conditions of chemical activity and temperature, significant dissolution of sulfide minerals and lesser dissolution of other associated minerals occurs in 12 hours. Under enhanced chemical conditions, this reaction time will be decreased. Thus, one pipeline section 20 miles (5.3 hours) long can chemically clean feed coal under enhanced reaction conditions. This section of the pipeline will be built of corrosion-resistant materials, perhaps steel pipe lined with ceramic or polymeric coatings. The location where coal cleaning is accomplished is selected for suitable conditions, especially water availability. During that step, ferric ion, acid, and oxygen would be introduced in appropriate concentration. Then after required residence time, mineralized solutions are flushed through a counter-current extraction loop to separate sulfur and other minerals from coal. Water requirements for this chemical processing system may be appreciable, although this water budget may replace some water now used during normal coal preparation, and power generation. Water management is critical in slurry transport systems (3).

Assuming that this system employs water-based slurry technology, the extraction possibilities are outlined in Figure 2. Acidity and redox potentials are controlled separately to set extraction conditions; moreover, these can be varied along this section. Aqueous acids or bases are added to adjust pH, and oxygen or hydrogen can be added to the transport system to change redox potentials. Alternatively, electrochemical reactions vary conditions. Conditions can be changed to any locus on the redox potential-acidity map (Figure 2). This system is bounded: basic conditions will precipitate iron oxides and other metals co-precipitate within the iron oxide flocculant. Basic conditions, therefore, are not suitable for dissolution but could be used to promote sulfur removal. Negative redox potentials result in homogeneous reduction of metallic elements, altering ions into less soluble redox forms [Fe (II) instead of Fe (III)]. Thus, the upper-left-hand quadrant is one initial locus for extraction process. The pipeline must be designed to survive these conditions. (Hard minerals, for instance the quartz fraction, might be solubilized initially under basic conditions. Then, without that hard component, erosion problems may be reduced and corrosion protection simplified.)

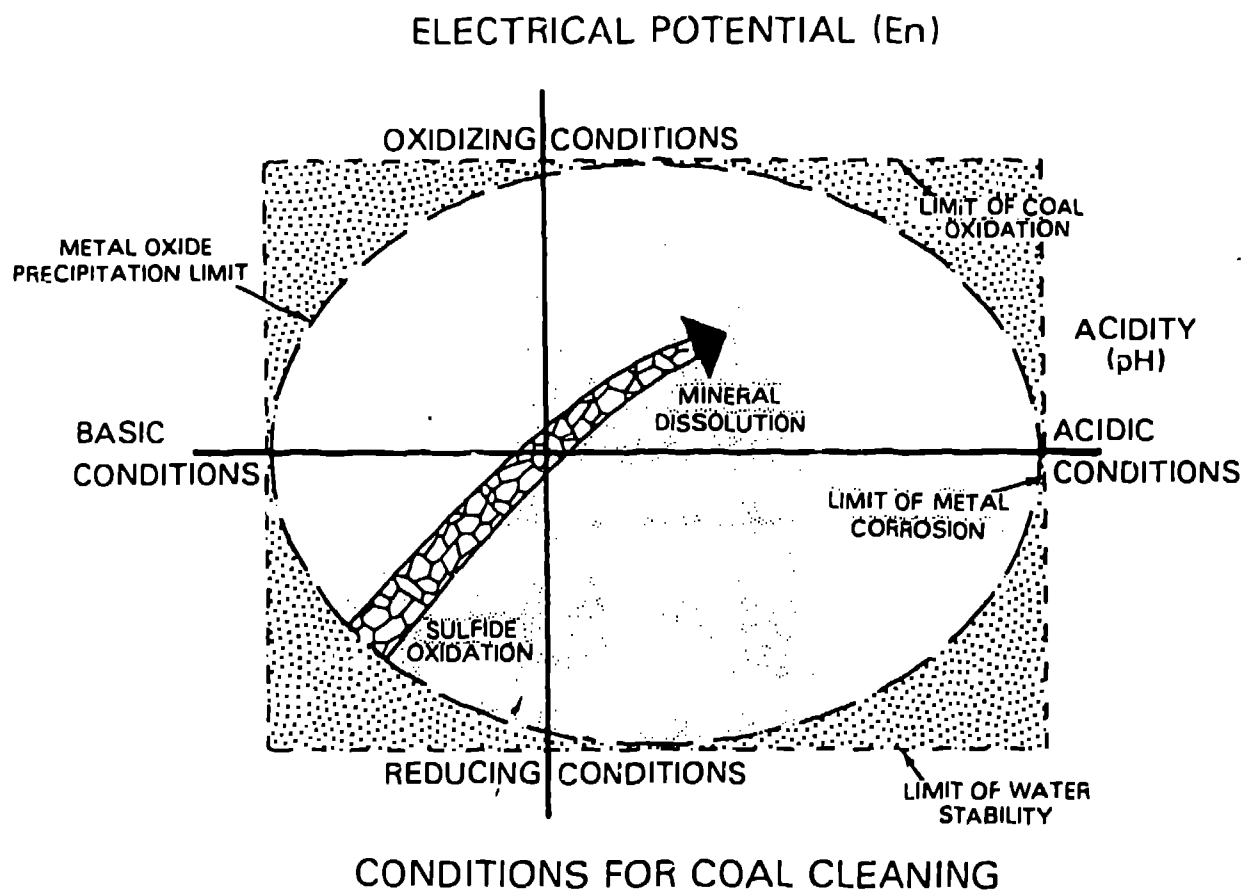


Figure 2 - Solution conditions suitable for extraction processes. Any location can be set on the pH, E_h diagram for specific mineral extraction; conditions can vary along the extraction section.

Following mineral extraction, coal is returned to neutral or reducing conditions to protect the heating content for the rest of the transport. In addition, although this will not be discussed in length, possibilities exist for chemical modification of the residual hydrocarbon-rich fraction into forms that are 1) more readily dewatered, 2) easily pumped into pressurized combustion or gasification reactors, and 3) have a higher BTU/pound content than the starting material.

The acidic, aqueous extract will include coal fines along with the mineralized solution. Volume of the extracts must be minimized to restrict costs. One possible extraction scheme is shown as Figure 3. Reactive aqueous solutions, probably sulfuric acid, Fe (III), and oxygen, are mixed into the slurry during transport through the "mineral removal section." The sulfur-oxygen reactions are sufficiently exothermic to raise process temperatures. (External heat sources may be required.) After the requisite residence time has been met, the solvent extraction chemicals are flushed through the slurry with counter-current flow. Following pH or other changes, the extraction process is repeated to effect additional recovery. Depending upon the chemical system chosen, several solvent extraction processes may be required. The coal fines, along with rejected anion species (mainly sulfates), are then neutralized, perhaps with calcium hydroxide or sodium carbonate, and the precipitated sludge and coal fines are discarded. This disposal step parallels current practice for disposal of waste from coal preparation plants or from power generation stations (FGD).

PIPELINE MINERAL EXTRACTION SYSTEM

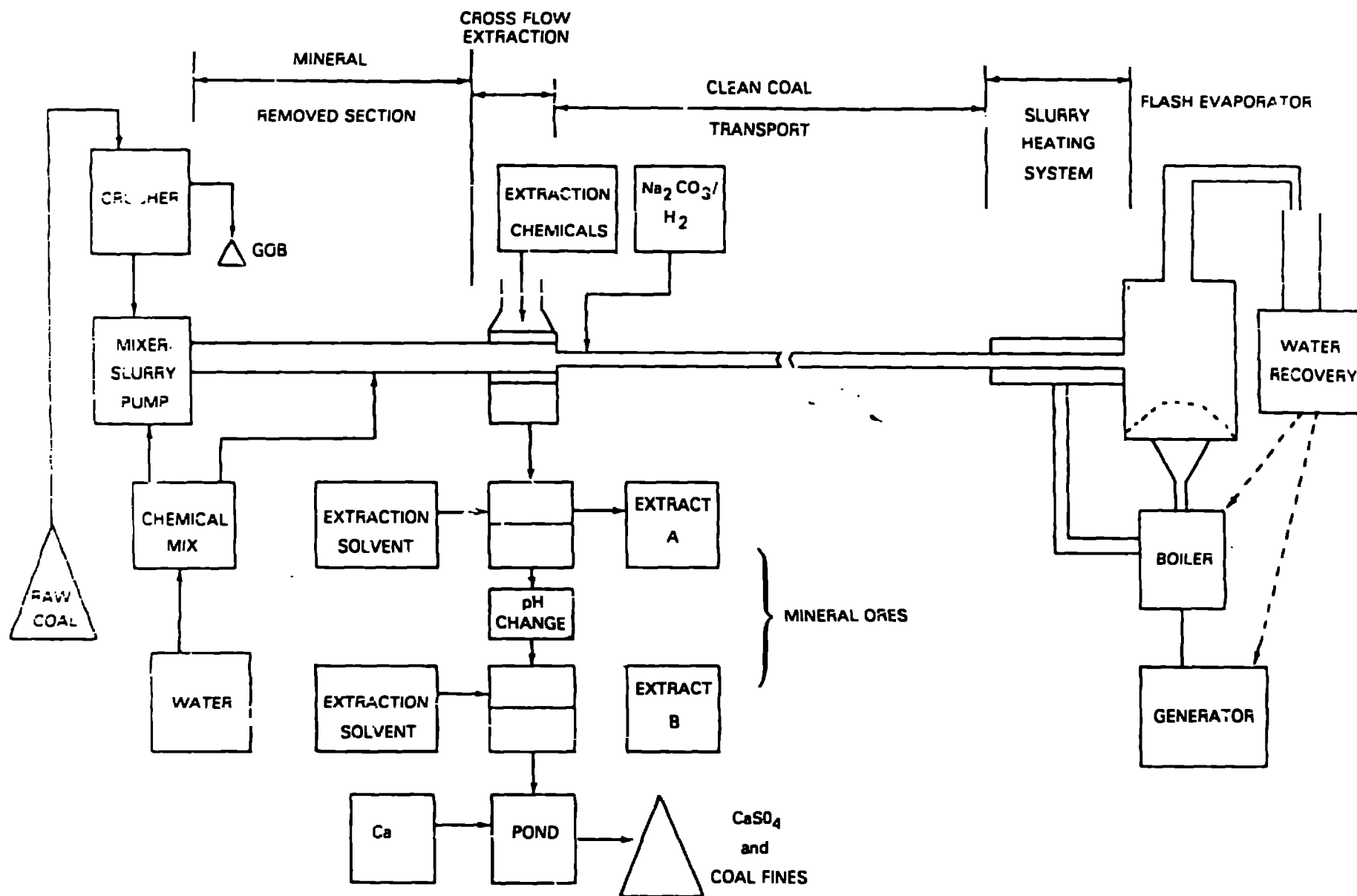


Figure 3 - General schematic of the coal transportation-mineral recovery scheme. Process shows solvent extraction processes for mineral removal from aqueous process streams. Extraction process can be positioned to take advantage of specific conditions.

The cleaned coal transport continues toward the utility market. Finally, in the vicinity of the generating station, waste thermal energy from that station is used to heat the slurry. At the terminus, pressures are lowered and the aqueous (or other solvent) fraction is evaporated, leaving a suitable, clean fuel for direct combustion or other uses. Obviously, water produced during this step has general utility. Alternatives are removing water with centrifugal drying or burning wet coal slurry. Water recovery from slurries generates additional mineralized solutions that may require waste water treatment before disposal. Direct combustion of the wet coal may require derating of the boilers.

Economics of Chemical Coal Cleaning During Slurry Transport

This proposed system generates quantities of mineral ores suitable for metal production. Although revenues from mineral operations contribute to system profitability, the majority of economic benefits result from coal transport-coal cleaning operations. This system primarily serves as a fuel transport device. Secondly, economic benefits arise from fuel upgrading; a higher quality fuel is produced during the transportation step. Mineral production is overshadowed by these other coal-technology economics. Even so, as shown in Table III, significant quantities of minerals could be produced annually from this model transport system.

Table III data show annual mineral recovery from 10^7 ton of coal, assuming a uniform 75% yield for each element listed. Of course, recoveries are dictated by extraction chemistry; most likely not all elements will be removed with this uniform efficiency. The highest tonnage recovery is iron. Assuming 75% removal, annual iron production is 1.3×10^5 tons. [If the pipe line (Table II) has a 1-inch wall thickness, the line requires 1.4×10^5 tons of iron. Annual iron production is sufficient to build

Table III. Recovery from Coal of Metals Important for Commerce

<u>Element</u>		<u>Concentration</u>	<u>Short Tons Produced/Year</u>
Iron	Fe	1.80 %	1.3×10^5
Titanium	Ti	0.07 %	5.3×10^3
Chromium	Cr	19. ppm	143
Cobalt	Co	8. ppm	60
Copper	Cu	16. ppm	120
Manganese	Mn	36. ppm	270
Molybdenum	Mo	6.4 ppm	48
Nickel	Ni	18. ppm	135
Uranium	U	1.5 ppm	11
Thorium	Th	3.3 ppm	25
Vanadium	V	35. ppm	262
Zinc	Zn	138. ppm	1035
Zirconium	Zr	46. ppm	345

Data assumes 75% recovery for a single slurry pipeline transporting 10,000,000 short tons annually.

another similar pipeline.] Chromium yields, annual recovery of 143 short tons (small compared to U.S. consumption, Table IV), contrast well with the chromium required to manufacture a new naval vessel, such as the Navy's new destroyer-escort series, 1.04 tons/ship (10). Thus, although mineral economics are dominated by economic benefits occurring from coal transportation, mineral production might be consequential when 1) numerous transport-extraction lines are in place, and 2) supplemental mineral ores are required.

Most likely, mineral prices will maintain trends set during the last years. Table V shows that gross revenues for the mineral production operation could be significant, assuming of course that production costs are low and that one can reduce iron solutions to metallic forms with favorable economics.

Table IV. Domestic Consumption and Production of Selected Metals^{8,10}

<u>Element</u>		(1)	(2)	(3)	(4)
		<u>Annual U.S. Consumption</u>	<u>Total Annual World Production</u>	<u>(1)/(2) x 100</u>	<u>Coal Production Total U.S. Consumption</u>
Silver	Ag	5.1	11.4	.45	0.07
Cobalt	Co	10.2	35.8	.29	0.59
Chromium	Cr	590.0	3168.0	.19	0.02
Nickel	Ni	239.8	738.4	.33	0.06
Molybdenum	Mo	33.9	108.4	.31	0.14
Niobium	Nb	3.3	12.0	.28	n/a
Titanium	Ti	19.8	51.5	.38	>1
Tantalum	Ta	0.6	0.4	1.50	>1
Tungsten	W	11.3	52.4	.22	0.54

Data are thousands of short tons.

- (3) Fraction of world production consumed in U.S.
 (4) Fraction of U.S. consumption possible from 100 slurry-transport systems (75% recovery).

Table V. Example of Mineral Revenues from Slurry Transport Recovery System

<u>Element</u>		<u>\$/Lb.</u>	<u>Annual Revenue</u>
Chromium	Cr	5.00	\$ 1.7 x 10 ⁶
Cobalt	Co	12.00	\$ 1.7 x 10 ⁶
Copper	Cu	1.50	\$ 4.3 x 10 ⁴
Molybdenum	Mo	11.00	\$ 1.3 x 10 ⁶
Nickel	Ni	2.00	\$ 6.5 x 10 ⁵
Uranium	U	35.90	\$ 9.15 x 10 ⁵
Iron	Fe	0.65	\$ 3.12 x 10 ⁸

Figure 4 contrasts two utility schemes that suggest why coal cleaning can impact electricity generation economics. Both schemes show a 10,000,000 ton/year transportation system powering a large coal-fired generation station. Significant capital and operating expense are required for FGD processes, necessary now to utilize many U.S. feed coals. Although modern coal preparation may help to lower overall capital costs (3), most existing physical coal cleaning processes are not sufficiently effective to eliminate stack gas cleanup. Cost estimates for FGD systems exceed \$400/kW installed generating capacity; thus, capitalization expense for a FGD system (2000-MWe station) approaches one billion dollars. Literature data show that chemical cleaning could result in sufficiently lower sulfur levels so that many U.S. coals can be burned without FGD systems. The long residence time coal cleaning conditions set within a slurry transport system permit thorough cleaning--cleaning is technically feasible. The economics of coal-derived electricity will reflect this technology.

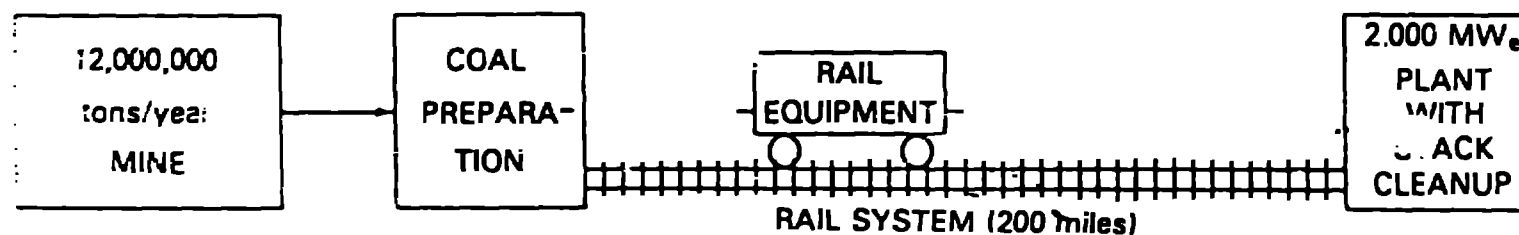
Transport is a second system cost advantage. Significant benefits accrue with slurry transport compared to surface-wheeled systems. Slurry system construction costs are less than half that of equivalent rail systems, not counting the cost of rail rolling stock, usually capitalized on other budgets (5,6). Thus, slurry transport contributes to cost benefits using the bottom scheme in Figure 4.

Mineral recovery, assuming current economics, may not add significant economic return to this slurry transport system. Costs may be excessive and any operational difficulties will impede income generation from the two important items--sulfur reduction and coal transport. Technologies for mineral recovery from low-grade ores are still under development. We cannot now project if minerals can be recovered following dissolution from coal minerals, let alone if processing is economic. However, even if mineral production only shows marginally improved economics, the advantages of mineral removal for new coal technology are of large import. Coal without mineral contaminants should be far more useful. It is also time to develop improved technologies that address low-grade ores, especially if those ores are to become reliable domestic sources for future metal requirements. Ideally, these technologies can be coupled to coal utilization, in ways that much of the development costs are derived through improvements in the coal utilization cycle. Then, as other low-grade mineral ores are exploited, for example Eastern oil shale, these same extractor technologies may serve for mineral recovery from these fuels as well as from coal. In the long term, production of metals may indeed result from coal, much like metal production (vanadium) from some petroloums.

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CASE ONE: CONVENTIONAL COAL-FIRED POWER PLANT (2,000 MW_e)



CASE TWO: SLURRY TRANSPORT SYSTEM WITH CLEANUP TO COAL-FIRED POWER PLANT (2,000 MW_e)

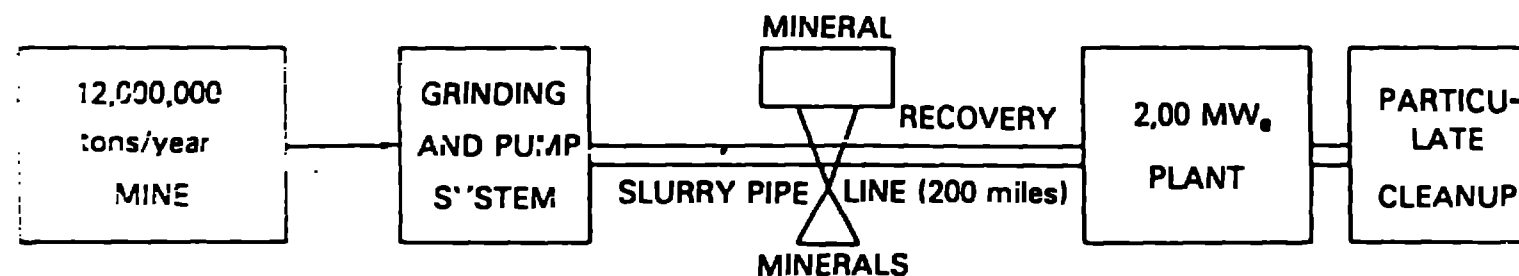


Figure 1 - Comparison of two mining, transportation, generation schemes for coal technology.

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